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USE OF PRESSURIZED MEMBRANES AS A LOW-COST ERECTION SCHEME FOR CONCRETE STRUCTURES

by

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INTRODUCTION

Thin concrete shells or folded plates are potentially an optimum system for enclosing or roofing individual or communal volumes in which lightweight, movable partitions could be used. It has been found that shell structures live up to this potential when large spans are enclosed. However, they are not competitive for small and intermediate spans because of the high erection costs associated with the conventional timber or steel formworks used in the casting of doubly curved concrete panels.

Investigations of more economical erection methods have been made (1, 2, 3, 4, 5). Some of these schemes have relied on the use of shot-creting techniques in the casting of the concrete. In the shot-creting process (6), the concrete slurry is sprayed, possibly overhead, at high velocity from a nozzle against a rigid or flexible formwork with the steel reinforcement either attached to or supporting the formwork. Drawbacks to such an erection technique for concrete shells have included (1) the limited range of geometric shapes and sizes of clear spans obtainable, (2) the lack of analytic capability to predict resulting formwork geometries and stresses, and (3) the lack of suitable materials (strength, durability, ductility, etc.) for use as formworks.

With recent advancements in materials technology and in the capability to accurately predict nonlinear membrane shell behavior, it has become possible to breathe new life into a scheme first developed by Wallace Neff in 1941, i.e. to spray concrete over the exterior or interior of an inflated plastic or rubber membrane. This technique has several intrinsic advantages: 1) the formwork in its conventional sense is eliminated and less labor is involved in the erection of the plastic replacement; 2) if the concrete were sprayed on the interior, the plastic shell would serve as weather protection during construction and could be left in place to provide subsequent weather-proofing for the concrete shell; 3) the plastic inflatable formwork would be light-weight and collapsible - the forms could be shop-produced; 4) the complex formwork necessary for a "free-form" shell would be more easily realized; 5) a large number of shell geometries could possibly be produced using a double-walled, compartmented form, and thus variations on a certain geometry could be erected using a single basic design for the formwork by inflating corresponding compartments in different forms to different pressures.

Early formworks of this type were designed using trial and error approaches. Only certain small shells could be obtained and, unfortunately, catastrophic collapses of the formwork during erection have been recorded in some instances. (2) Solution methods have now been developed with which it is possible to accurately predict the displacements and stresses for an inflatable shell during the various stages in the shotcreting process. It is also possible to predict the initial shape of a deflated formwork required to obtain a close approximation to any desired configuration for the final concrete shell.

A single multi-purpose computer program has been developed to analyze various aspects of the inflation process for arbitrary shells of revolution: intermediate inflation configurations and stress states are predicted; static and dynamic responses to nonsymmetric external loads are predicted. Numerical solutions are generated even for shells of revolution which only have pointwise coordinates of the meridian specified rather than the exact algebraic equation.

A finite element analogue for the nonlinear response of "free-form" shells has been developed. (12) Either a multi-step, incremental approach or a single-step, iterative approach can be used. The single-step method is useful when it is desired to calculate the required initial shape to obtain a final formwork shape after all pressure and concrete have been applied. The multi-step method is useful when it is the initial shape which is known a priori. The two approaches can be used in tandem to predict the response of full-loaded formworks to further external loads.

Complete discussions of these solution methods are given in References 7 through 11 along with a number of examples. The example given herein is intended to demonstrate the field cost feasibility of the proposed construction scheme. A detailed construction process for one sample roof shell is given along with a complete deformation and stress analysis of the formwork during erection. A crude cost comparison of the conventional technique with the proposed technique is given for that example.

MATHEMATICAL AND PHYSICAL DESCRIPTION OF FORMWORK BEHAVIOR

For convenience in the description of the complete physical behavior of inflatable formworks and also in the development of a mathematical analogue, the behavior of an inflatable shell was considered to be divided into two primary stages: 1) the pressurization phase in which the shell undergoes large displacements under the action of internal pressure from an unstressed initial state into a final design configuration; and 2) the in-service phase wherein additional external loads, the weight of uncured concrete in this instance, are applied which induce further small displacements.

The assumptions made in the analysis of the pressurization phase are that 1) the form material is elastic and isotropic, 2) the form is extremely thin and therefore possesses negligible bending rigidity, and 3) the final deformed middle surface can be used as the reference surface for all stresses and displacements. As a consequence of these assumptions, the equilibrium equations for the shell are statically determinate and direct solutions for the stresses can be obtained. Also, by means of the Poincare perturbation technique (7) the displacements can be obtained recursively from the exact solutions of an infinite set of convergent linear differential equations. The sum of these linear displacement components can then be used to calculate the shape of the original membrane required to attain the desired final configuration.

The in-service phase can be considered as the superposition of a linear problem onto the previous nonlinear problem posed by the pressurization phase if one makes the additional assumption that the initial pressurization has stiffened the shell sufficiently that any additional deformations are small. For this case a linearized theory has been developed (8) which, unlike classical linear theory, incorporates the effects of the initial pressurization stress in the governing equations of equilibrium. (9, 12)

Any one of a number of numerical solution schemes can be used on these equations to obtain the additional in-service displacements. From these the additional stresses can be obtained by back-substitution into the stress-displacement relations. The additional displacements are superposed onto the design configuration of the formwork in order to calculate the amount of deviation of the membrane from the desired shape due to the weight of uncured concrete. It is possible to consider a sequence of incremental in-service loadings (as in the spraying of several layers of concrete) by continually updating the shape of the reference surface.

EXAMPLE PROBLEM

The problem chosen to illustrate the application of the solution methods described previously is that of the design of a formwork for a segment of a spherical dome to be used as a cap for a one million gallon cylindrical water tank as detailed in Chap. 4 of

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Ref. 13. The dimensions of this 88.5 ft. span dome are given in Figure 1. More detailed dimensioning and reinforcement details are given in Ref. 13. This example was selected because 1) its size corresponds to an intermediate span; 2) detailing data were readily and generally available; and 3) it was possible to estimate the cost of construction for this dome for both the conventional method and for the proposed method. The fact that the example is that of a spherical dome for a water tank is not detrimental. The principles of analysis, the construction methods, and cost estimates are equally valid for other shapes for other applications.

The design of the formwork for this shell is an interactive process between analysis, design, and detailing. After preliminary estimates of the construction process (described subsequently) a mathematical analysis of form behavior is made. Based on the results of the analysis, final details of the construction process are then made.

It is assumed that the deflated formwork will be placed on horizontal scaffolding attached to the top of the cylindrical tank and inflated to an initial pressure of 0.75 psi while the weighted edges of the form are allowed to slide along the scaffolding to vertical stops mounted at the cylindrical edge. Then consecutive rings of concrete of the required thickness are sprayed onto the formwork progressing from the edge up towards the crown. Simultaneously the internal pressure is increased gradually to a maximum of 1.00 psi. This was done to partially offset the deformations induced by the dead weight of the applied concrete thus minimizing the deviations from the perfect sphere desired.

The schedule of loading increments provided the input data to the computer to calculate the various configurations and stresses for the formwork during shotcreting. Three configurations assumed by the formwork during erection are shown in Figure 2. Also shown

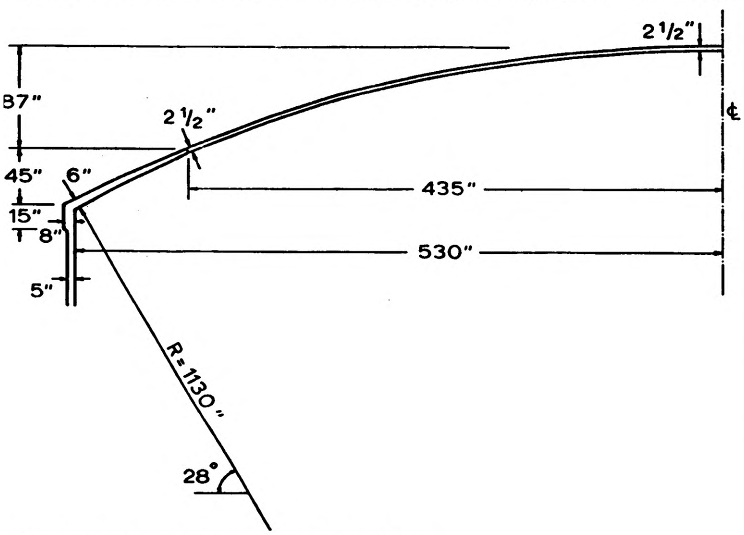

Fig. 1. Geometry and Dimensions of Spherical Cap

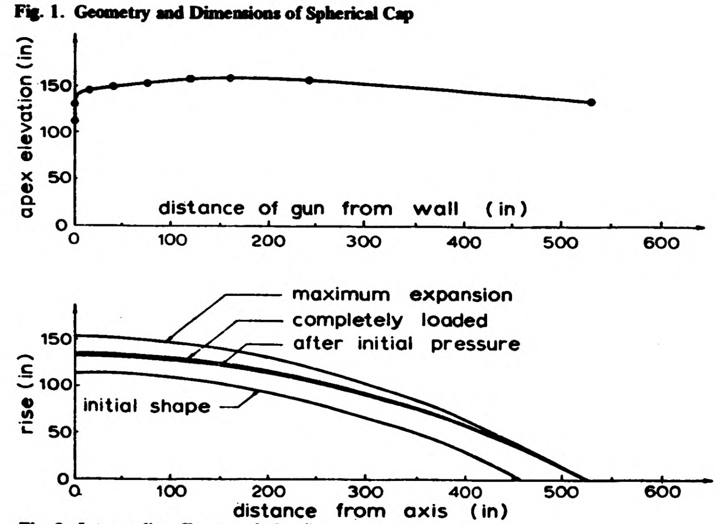

Fig. 2. Intermediate Formwork Configurations and Gun Location

is a plot of the crown elevation as a function of current location of the gunning operation. It can be seen that the shell geometry after completion of casting is a close approximation to the desired spherical shape. At all times in the erection process the stresses were less than 2/3 of the advertised bursting strength of the commercially available fabric (a single ply, vinyl-coated, nylon fabric) assumed in the analysis. The stress and displacement results of the computer analysis were used to detail the construction process.

Once the initial meridional curve has been calculated, the shell can be fabricated by first stitching together strips of plastic so as to form conical frustra and by joining the frustra together to form an approximation to the dome shape. Assuming a standard roll width of 54 inches and accounting for 6 inch overlaps, one can use the computer results to calculate the number and sizes of strips required. For this example, 11 strips were required for the dome (2 additional strips are needed as discussed subsequently). The dimensions and cutting patterns were selected so as to minimize wastage.

The assembled form is laid out on the inner edge of scaffolding extending at least 73 inches (from computer results) inward from the cylindrical wall. It is necessary to provide weights at the edge of the form. This is obtained by adding two more strips to the form and lapping them so as to form a circular tube 27 inches in diameter which is then filled with water. The size of the tube is calculated as follows: 1) the edge tension developed during pressurization is 450 lb/ft acting at an angle of 28°; 2) the vertical component 211 lb/ft is balanced by 4 ft^3/ft of water with a density of 62.4 lb/ft^3 (total of 250 lb/ft provided); 3) 4 $ft.^2$ of area requires a 27 inch diameter tube.

The horizontal component of edge tension is counterbalanced by wire cables attached to the water tube at 15.5 ft. intervals and leading through the stops mounted at the cylindrical edge to winches at ground level. Based on a horizontal component of 397 lb/ft plus a friction force between the water tube and scaffolding of 125 lb/ft (= 0.5 x 250 lb/ft vertical force), each winch and cable must provide a force of 8100 lbs.

The interior is then pressurized to 0.75 psi by two 10,000 cfm centrifugal blowers while simultaneously winding the cables on the winch until the water tube is contiguous with the vertical stops at the circular edge wall.

A gunning crew (foreman, delivery equipment operator, nozzleman, and assistant) then spray one inch of high-early strength concrete onto the dome using a pneumatic feed, wet-mix gun and a 125 cfm air compressor. After three to four hours hooks are nailed to the cured concrete and the steel reinforcement is attached. Templates for subsequent gunniting are also placed at this time. Final spraying of consecutive rings is done to build up the required thickness of the tapered dome. As each ring is sprayed the internal pressure is increased, as discussed previously, to a total of 1 psi.

A comparison of costs of the proposed new method of construction and the conventional method is given in Tables 1 and 2. It can

TABLE 1: CONSTRUCTION COSTS USING CONVENTIONAL METHOD

	Quantities		Unit Prices		Amounts	
	Total	Unit	Inst.	Mat.	Inst.	Mat.
Dome Forms (2 uses)						
plyform + bracing + accessories	74.2	100 SF	72.05	33.12	5346	2458
Interior scaffold rental	1700.0	100 SF	3.50	0.65	5950	1105
Exterior scaffold rental	78.7	100 SF	13.50	5.80	1063	457
Concrete (1:2:4) ready-mix in place	62.4	CY	7.15	18.00	446	1123
Structural Steel Bars	2.0	tons	175.00	260.00	350	520
Structural Steel Mesh (6x6x6/6 welded)	73.7	100 SF	3.65	3.40	269	251
Finishing	65.8	100 SF	0.06	-	4	-
Curing	65.8	100 SF	1.75	0.75	115	49
		TOTALS			$13543	$5963

GRAND TOTAL = $19,506.

TABLE 2: CONSTRUCTION COSTS USING PROPOSED METHOD

	Quantities		Unit Prices		Amounts	
	Total	Unit	Inst.	Mat.	Inst.	Mat.
Dome Forms (2 uses)						
Material	618-1/3	yds.	-	2.24	-	1385
Cutting	20	cuts	1.25	-	25	-
Assembly	-	-	Lump	Sum	500	-
Interior scaffold and platform	59	100 SF	13.50	5.80	796	342
Pressurization-Grouting, + blowers, + winches, + placement	-	-	Lump	Sum	2500	-
Shotcreting (20% waste)	6580.0	SF	0.70	0.65	4606	4277
Structural Steel Bars	2.0	tons	175.00	260.00	350	520
Structural Steel Mesh	73.7	100 SF	3.65	3.40	269	251
Finishing + Curing	65.8	100 SF	1.81	0.75	119	49
		TOTALS			$9165	$6824

GRAND TOTAL = $15,989.

be seen the proposed method has a cost savings of $3517, or 18% of the conventional method. All cost estimates were obtained from Ref. 14.

In the conventional method the major cost items are 1) the interior scaffolding required to brace the form and 2) the plyform panels to fabricate the contact area of the form. Considerable labor and wastage of material is involved in the construction of the curved formwork from the flat plyform panels. In the proposed technique the primary cost item is the shotcreting expense. The unit costs given here for shotcreting are average figures provided by different sources. However, they do include corrections for labor and material wastage for overhead gunning. The labor costs in both estimates include stripping as well as erection costs and in both instances two uses of the forms were assumed.

CONCLUSION

The advantages and cost feasibility of the use of inflatable formworks for the erection of concrete domes have been given and illustrated by a complete example of a spherical concrete cap with a clear span of 88.5 ft. The use of inflatable forms eliminates the necessity of filling large volumes with scaffolding in order to brace the formwork. It also reduces the amount of field labor required to construct the curved contact area of the formwork.

Using recently developed mathematical techniques, one can accurately predict the fabricated shape for the fabric formwork required for the erection of any prescribed concrete shell geometry. Stress levels in the formwork can be predicted for all stages in the erection process. Also the response, static or dynamic, of the formwork to expected environmental loads, snow, wind, etc., can be accurately determined.

Several aspects of the proposed building technique need to be explored experimentally before the cost and field feasibility of the technique can be completely established. Chief among these would appear to be the characteristics of the bond between the gunned concrete and the coated fabric. The fabrics are typically coated with vinyl, a material which is not effectively wetted by water. The bond between these two materials then would potentially seem to be comparatively weak. Various factors could be investigated, such as 1) the inclusion of a wetting agent in the concrete mix, 2) a static electric treatment of some sort of the fabric, or 3) the form could be sprayed with an asphaltic mix prior to shotcreting. Study of this aspect of the problem should include an allowance for the fact that the inflated form will not be stationary as the concrete is applied but will probably be subjected to substantial dynamic local displacements because of the force generated by the application of the concrete.

Another area which has not been investigated sufficiently is the environmental stability of the coated fabric itself. This becomes particularly significant if it is decided to leave the insulated fabric in place as weatherproofing over the concrete dome after the concrete has achieved its design strength. Many polymeric materials including the vinyls are, for example, subject to deterioration upon prolonged exposure to ultra violet light. It has been demonstrated, however, that the requisite analytical capability for the design of such formwork exists and preliminary research points toward the economic feasibility of the use of inflatable formwork as an alternative erection scheme for concrete structural systems in the urban environment.

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